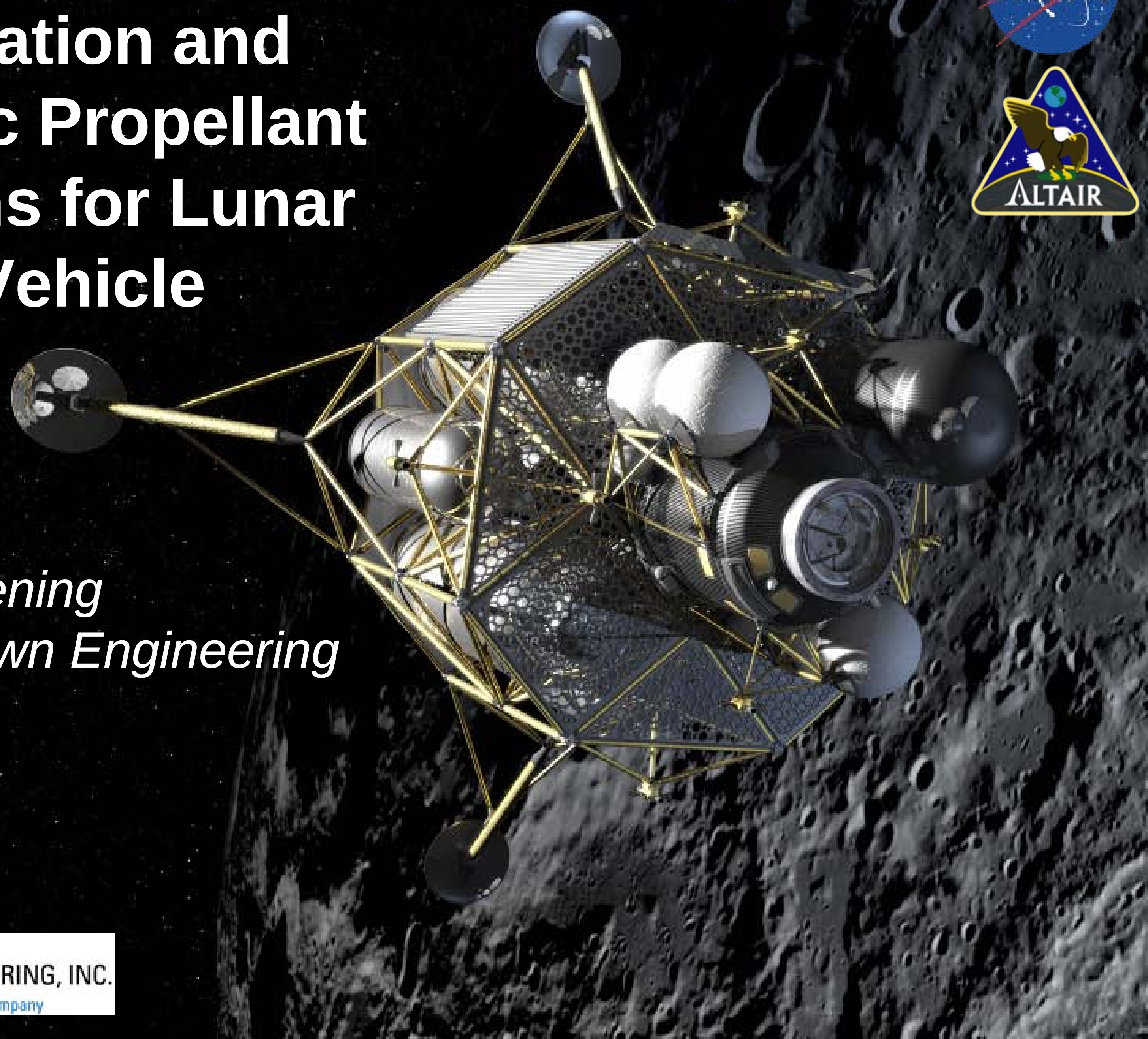
Analytic Modeling of Pressurization and Cryogenic Propellant Conditions for Lunar Landing Vehicle



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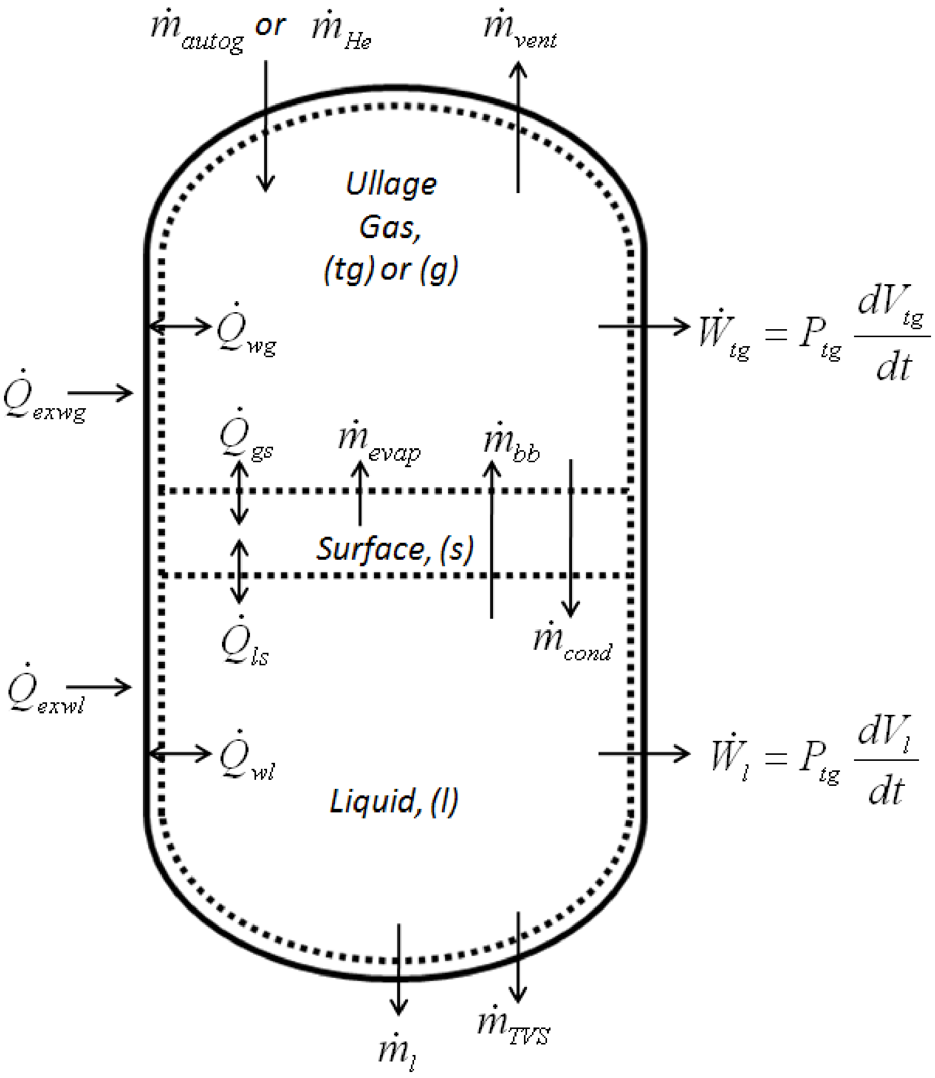
Presentation Outline

- Computational Propellant and Pressurization Program – One Dimensional (CPPPO) Model Development
  - Define Control Volumes
  - Various Model Information
  - Conservation Equations
  - Heat and Mass Transfer
- CPPPO Model Validation
  - Conservation of mass and energy internal to model
    - Validated during all scenarios for heat and mass transfer
  - Comparison to existing analytic model
    - ROCETS used for design of Ares I Upper Stage
  - Flight Experiment
    - AS-203 (S-IVB stage orbital test)
  - Ground Experiment
    - NASA Glenn LH_2 tank self pressurization testing
- Application to Lunar Landing Vehicle (currently named Altair)
  - Parametric analysis on pressurant conditions
  - Unequal tank pressurization and draining for multiple tank designs

Cryogenic Propellant and Pressurization Modeling

CPPPO Model Development

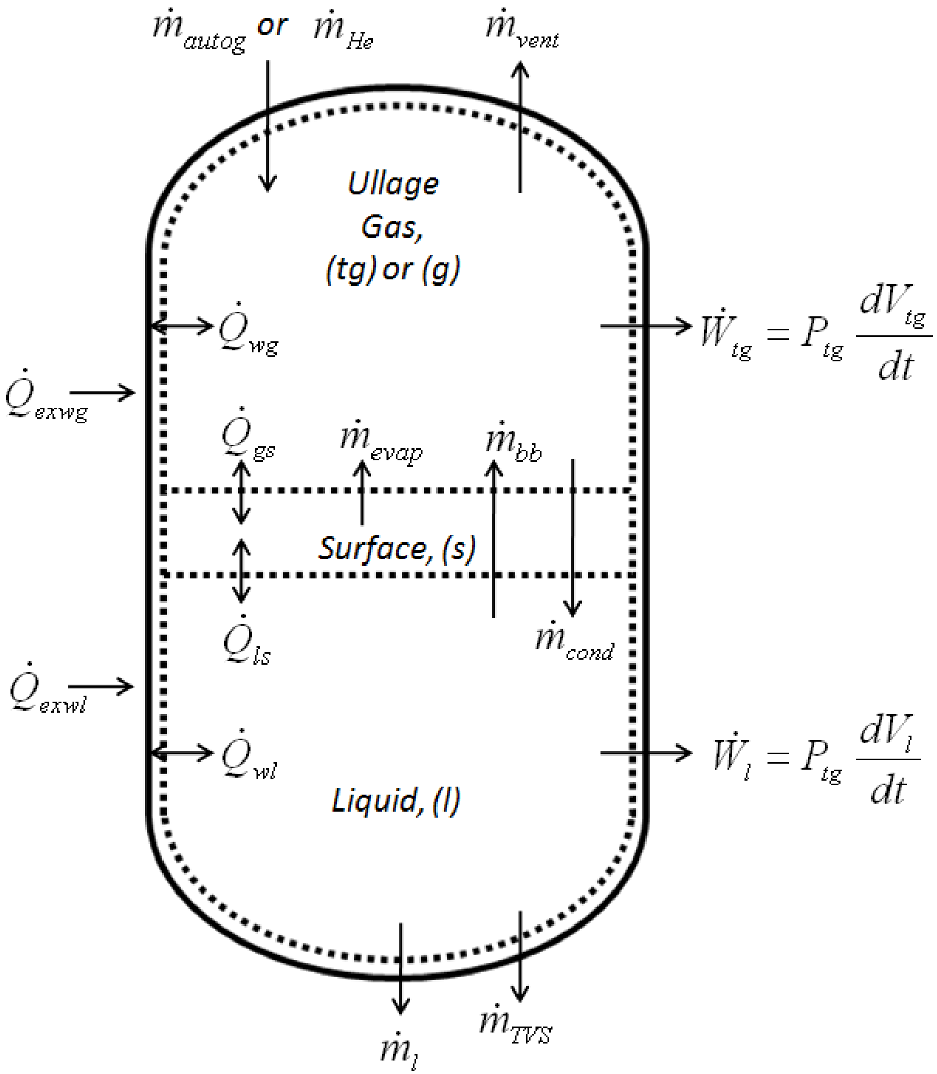
- Control Volume Definitions
  - Ullage gas: mixture of propellant vapor and Helium pressurant
  - Surface: infinitely thin layer containing no mass at propellant saturation conditions (used to pass heat between ullage and liquid and allow for surface layer evaporation)
  - Liquid: liquid propellant remaining in tank
- 5 Node Model
  - Tank wall exposed to ullage gas
  - Ullage gas
  - Surface layer
  - Liquid
  - Tank wall exposed to liquid



CPPPO Model Development

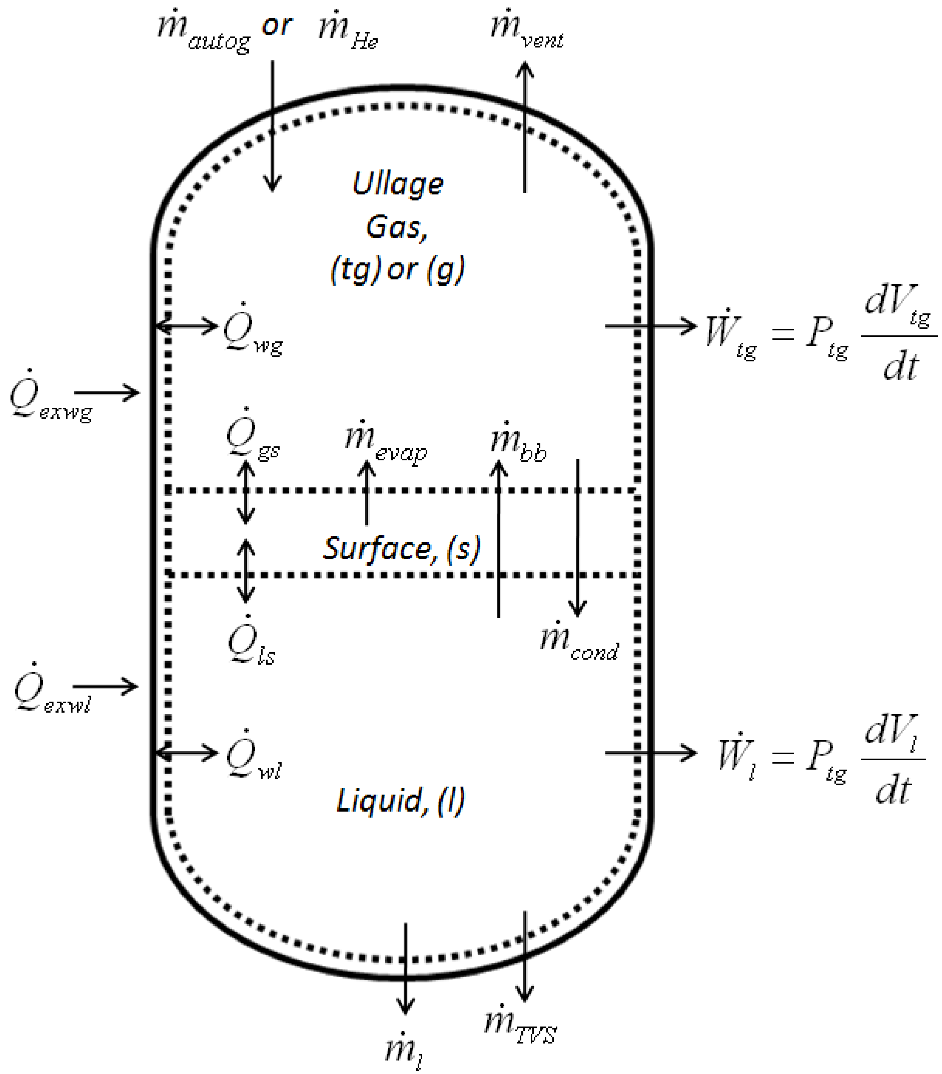
- Variable Definitions

Variable	Units	Definition
$\dot{m}_{autog}$	lbm/s	Autogenous GH2 or GO2 pressurization mass flow rate
$\dot{m}_{He}$	lbm/s	Helium pressurization mass flow rate
$\dot{m}_{vent}$	lbm/s	Vent relief mass flow rate
$\dot{Q}_{exwg}$	Btu/s	Heat transfer rate from external environment to metallic tank wall skin exposed to ullage gas node
$\dot{Q}_{wg}$	Btu/s	Heat transfer rate between ullage gas node and tank wall exposed to ullage gas node
$\dot{Q}_{gs}$	Btu/s	Heat transfer rate between ullage gas node and saturated surface layer node
$\dot{m}_{evap}$	lbm/s	Propellant evaporation mass flow rate
$\dot{m}_{bb}$	lbm/s	Propellant bulk boiling mass flow rate
$\dot{W}_{tg}$	lbf-ft/s	Ullage gas node work rate
$\dot{Q}_{exwl}$	Btu/s	Heat transfer rate from external environment to metallic tank wall skin exposed to liquid node
$\dot{Q}_{wl}$	Btu/s	Heat transfer rate between liquid node and tank wall exposed to liquid node
$\dot{Q}_{ls}$	Btu/s	Heat transfer rate between liquid node and saturated surface layer node
$\dot{m}_{cond}$	lbm/s	Propellant vapor condensation mass flow rate
$\dot{W}_{l}$	lbf-ft/s	Liquid node work rate
$\dot{m}_{l}$	lbm/s	Propellant liquid mass flow rate
$\dot{m}_{TVS}$	lbm/s	Propellant Thermodynamic Vent System (TVS) mass flow rate
P_{tg}	psia	Tank Pressure
V_{tg}	ft³	Ullage gas volume
V_{l}	ft³	Liquid volume



CPPPO Model Development

- Various Model Information
  - Finite Difference method
  - All fluid properties updated at each time step using NIST Refprop
  - All internal tank heat transfer is Free Convection
  - Helium pressurant tank assumed isentropic blowdown
  - Tank wall is modeled as a lump thermal mass
  - External heat transfer rates assumed averaged over exposed tank surface area
  - Simplistic Thermodynamic Vent System (TVS) modeled during any in-space coast phases



CPPPO Model Development

- Conservation Equations
  - Ullage Gas:

$$\dot{Q}_{gs} - \dot{Q}_{wg} + \dot{m}_{autog} h_{autog} + \dot{m}_{He} h_{He} + \dot{m}_{evap} h_{evap} + \dot{m}_{bb} h_{bb} - \dot{m}_{cond} h_{cond} - \dot{m}_{vent} h_{tg} - P_{tg} \frac{dV_{tg}}{dt} = \frac{d}{dt}\left(m_{tg} u_{tg}\right)$$

  - Applying Ideal Gas assumption to internal energy in ullage:

$$m_{tg} C_{v_{tg}} \frac{dT_{tg}}{dt} = \dot{Q}_{gs} - \dot{Q}_{wg} + \dot{m}_{autog}\left(h_{autog} - C_{v_{tg}} T_{tg}\right) + \dot{m}_{He}\left(h_{He} - C_{v_{tg}} T_{tg}\right) + \dot{m}_{evap}\left(h_{evap} - C_{v_{tg}} T_{tg}\right)$$

$$+ \dot{m}_{bb}\left(h_{bb} - C_{v_{tg}} T_{tg}\right) - \dot{m}_{cond}\left(h_{cond} - C_{v_{tg}} T_{tg}\right) - \dot{m}_{vent}\left(h_{tg} - C_{v_{tg}} T_{tg}\right) - P_{tg} \frac{dV_{tg}}{dt} - m_{tg} T_{tg} \frac{dC_{v_{tg}}}{dt}$$

  - Pressure and Volume rate of change:

$$P_{tg} = \rho_{tg} R_{tg} T_{tg}$$

$$\dot{V}_{tg} = \dot{V}_{l} + \frac{1}{\rho_l}\left(\dot{m}_{bb} + \dot{m}_{evap} + \dot{m}_{TVS} - \dot{m}_{cond}\right) - V_l \frac{\dot{\rho}_l}{\rho_l}$$

CPPPO Model Development

- Conservation Equations
  - Liquid:

$$\dot{Q}_{wl} - \dot{Q}_{ls} + \dot{m}_{cond} h_{cond} - \dot{m}_{bb} \Delta h_v - \dot{m}_{bb} h_{bb} - \dot{m}_{TVS} h_{TVS} - \dot{m}_l h_l - P_{tg} \frac{dV_l}{dt} = \frac{d}{dt}(m_l u_l)$$

  - Apply internal energy and enthalpy relationship to get:

$$m_l \frac{dh_l}{dt} = \dot{Q}_{wl} - \dot{Q}_{ls} + \dot{m}_{cond}(h_{cond} - h_l) - \dot{m}_{bb} \Delta h_v - \dot{m}_{bb}(h_{bb} - h_l) - \dot{m}_{TVS}(h_{TVS} - h_l) + V_l \frac{dP_{tg}}{dt}$$

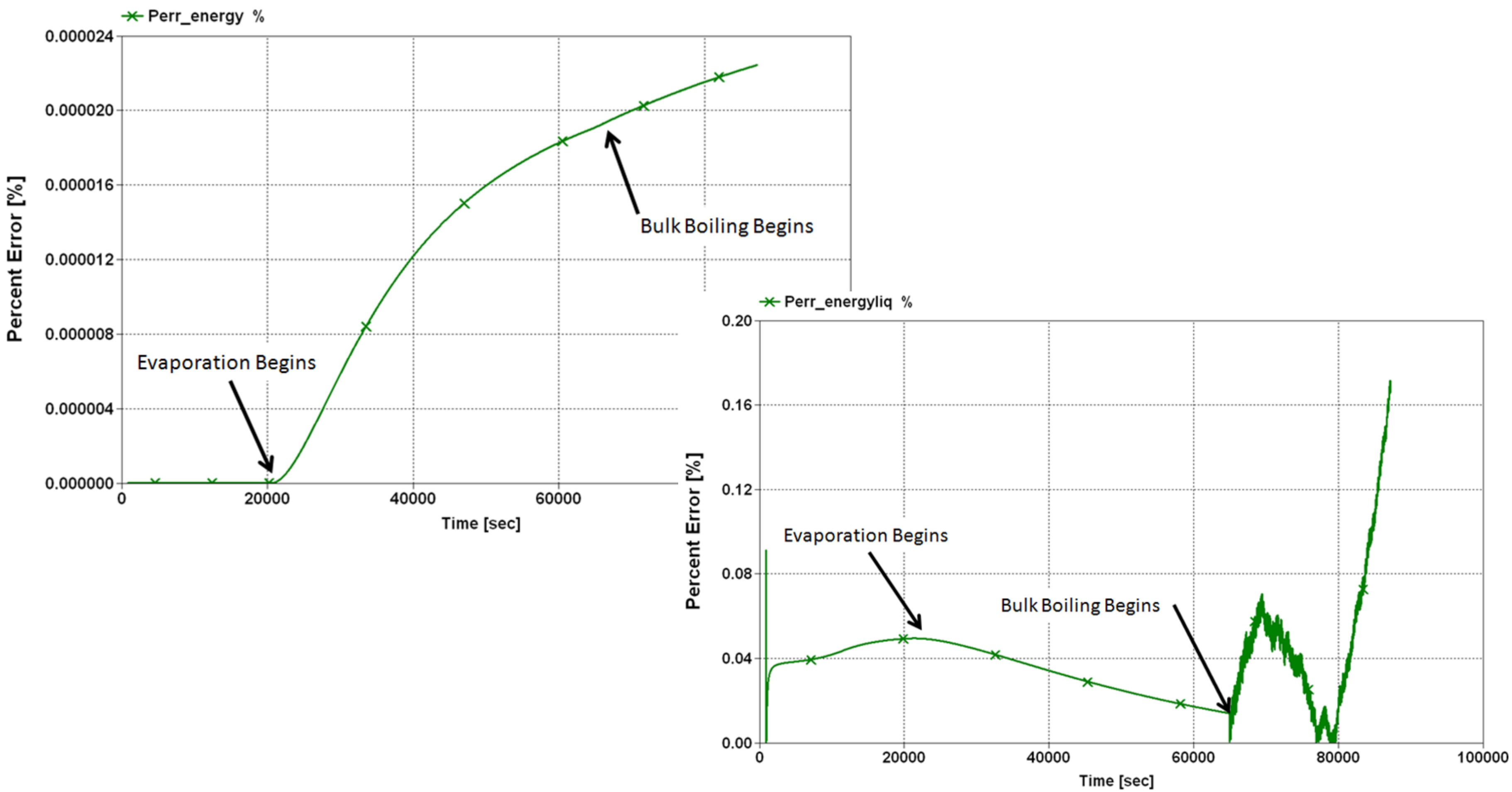
  - Therefore, liquid propellant remains a real fluid.
  - This is very important for LH_2 during in-space coast phases since it is highly compressible, contracting and swelling from pressure and heat.

CPPPO Model Development

- Heat Transfer
  - Internal Tank Heat Transfer is all in form of Free Convection
    - During rapid pressurization this assumption breaks down due to forced convective motion of pressurant gas in ullage
    - However, these time scales are minimal compared to the burn duration and coast times of interest
  - Free Convection coefficient and exponent taken from standard text with acceleration vector parallel and normal to plane
- Mass Transfer
  - Included in form of evaporation, bulk boiling, and condensation
  - Certain conditions must be achieved before any form of mass transfer occurs
- Heat and Mass Transfer are most difficult to validate
  - Limited data exists for pressure rise in closed tanks however the method of heat transfer (free/forced convection, conduction) and mass transfer (evaporation, bulk boiling, condensation) causing such a pressure rise is difficult to pinpoint

CPPPO Model Validation

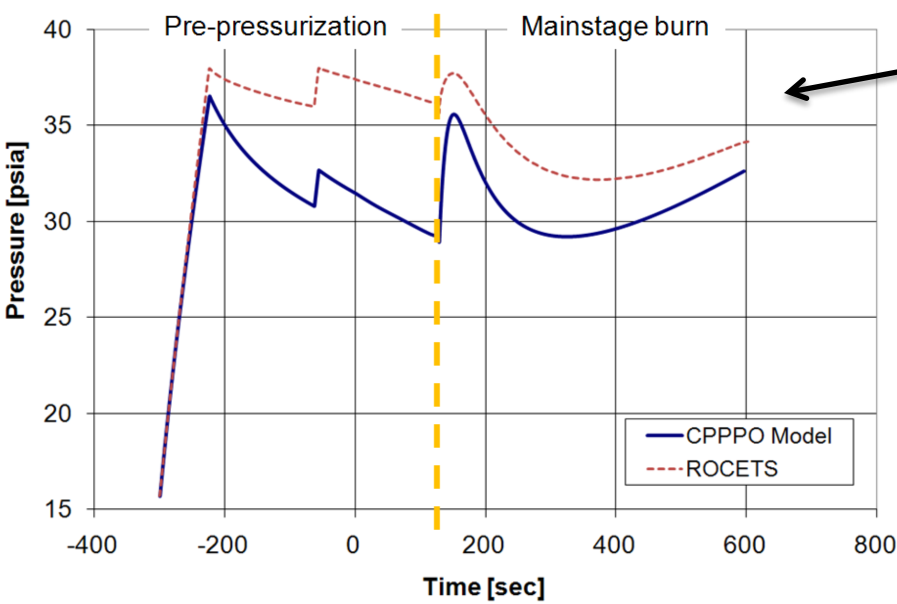
- Conservation of mass and energy internal to model
  - Validated during all scenarios for heat and mass transfer



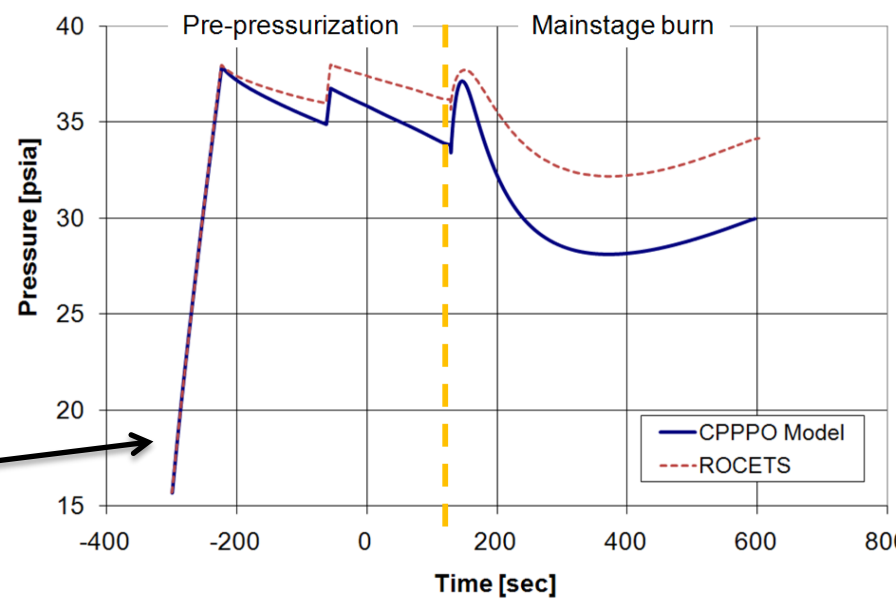
Cryogenic Propellant and Pressurization Modeling

CPPPO Model Validation

- Comparison to existing analytic model
  - ROCETS used for design of Ares I Upper Stage
  - LH_2 Tank Examples



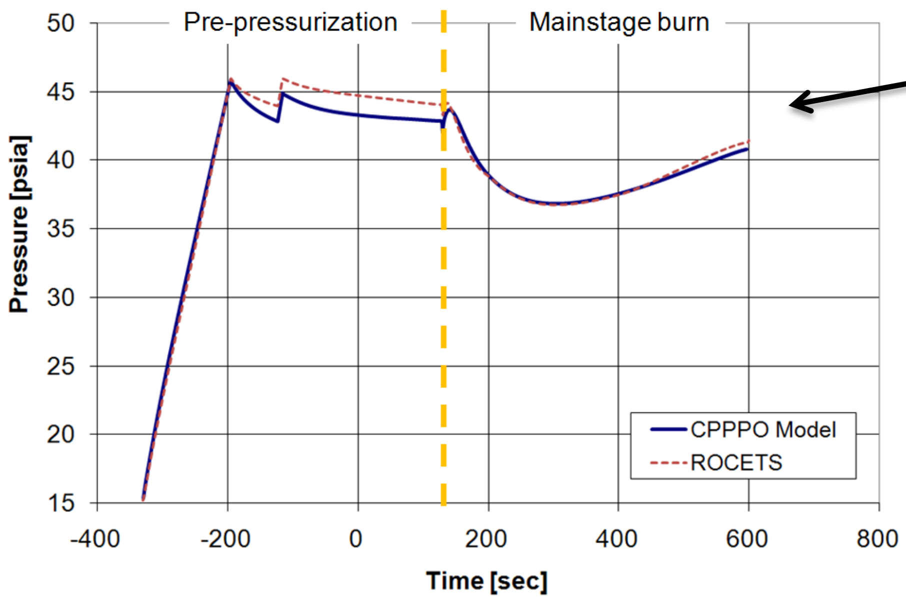
Using CPPPO Model calculated heat transfer rates



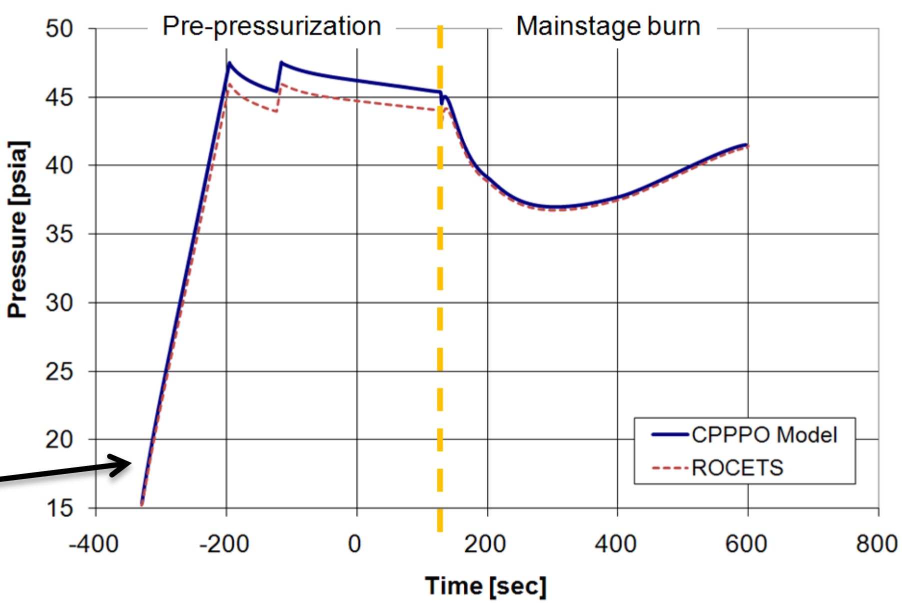
Forcing ROCETS calculated heat transfer rates

CPPPO Model Validation

- Comparison to existing analytic model
  - ROCETS used for design of Ares I Upper Stage
  - LO_2 Tank Examples

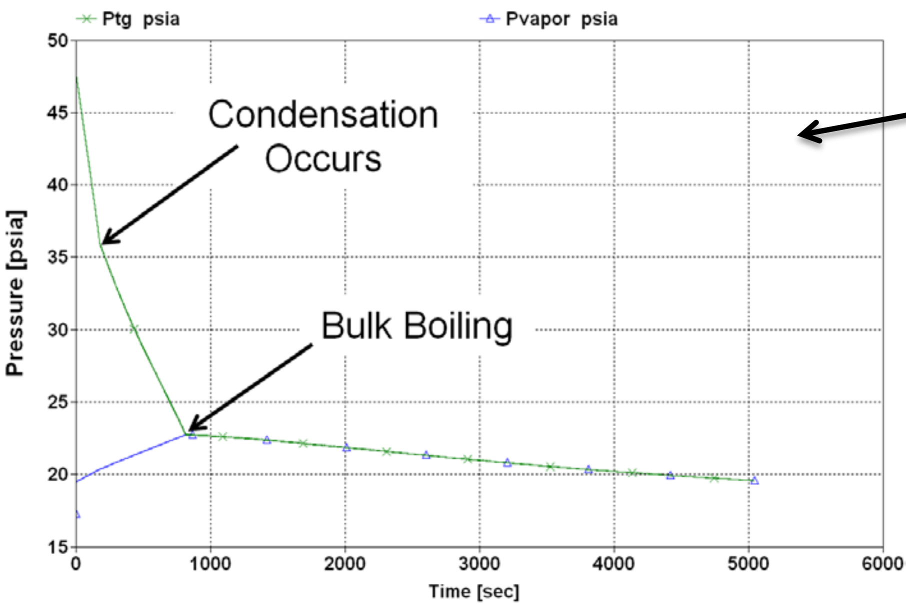


Using CPPPO Model calculated heat transfer rates

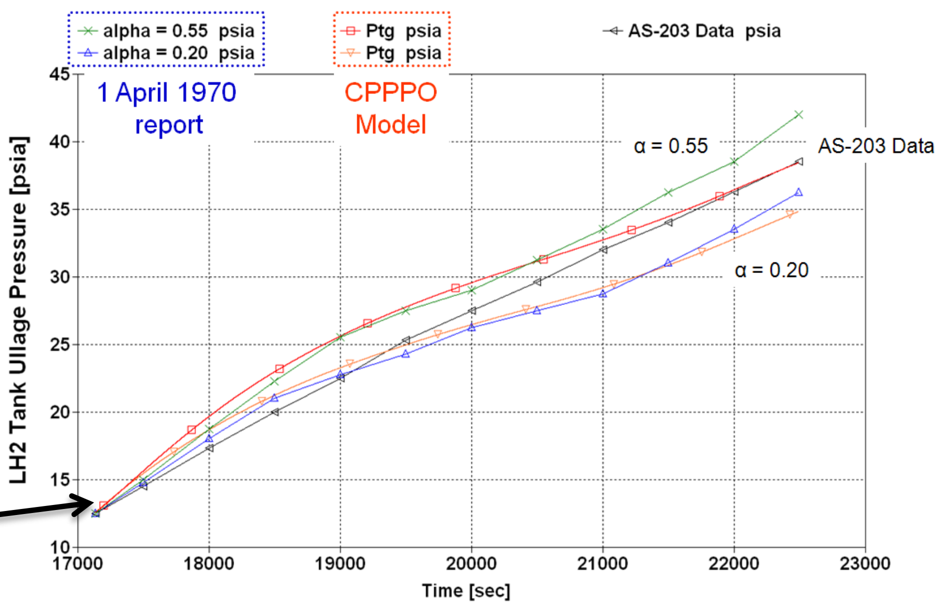


Forcing ROCETS calculated heat transfer rates

- CPPPO Model Validation
  - Flight Experiment
    - AS-203 (S-IVB stage orbital test, LH_2 tank results)



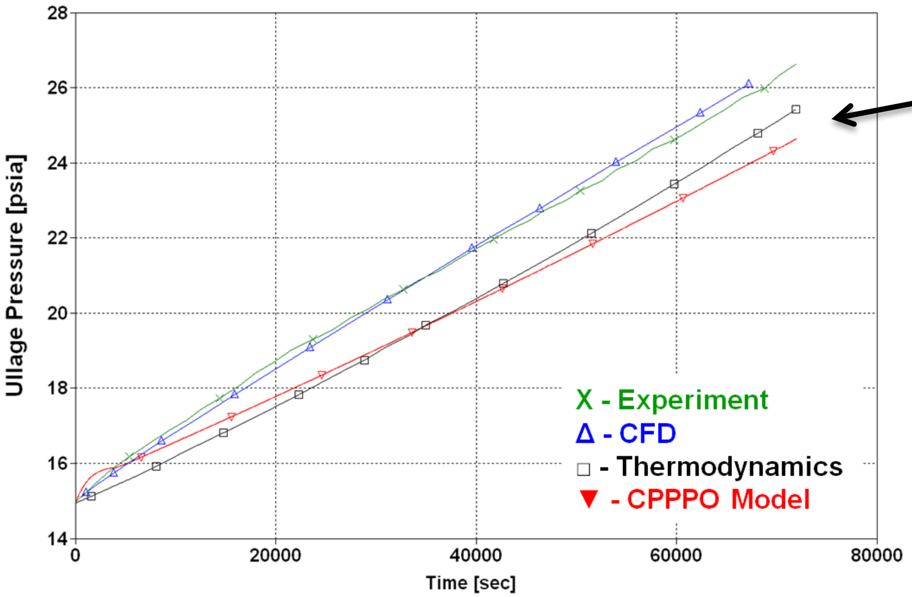
Continuous vent comparison: remained around 20 psia



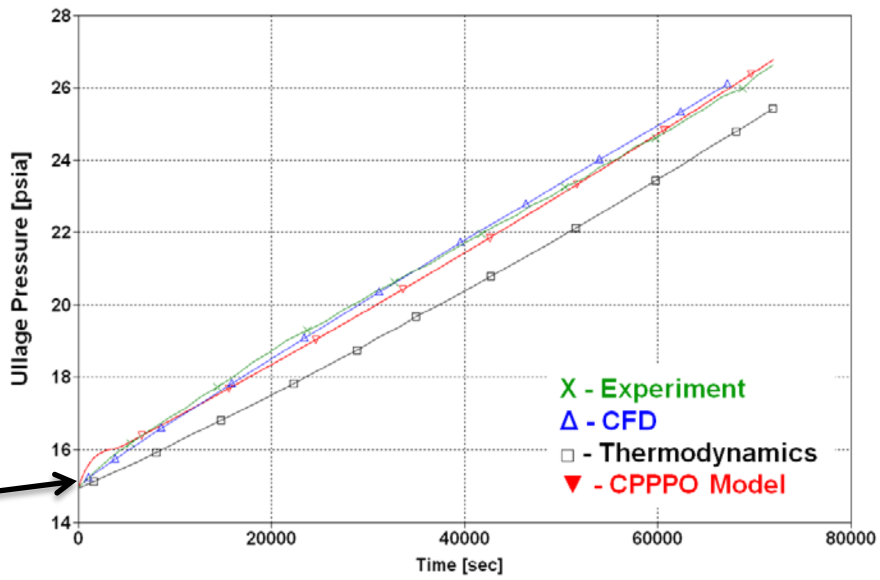
Closed tank pressure rise comparison: very good correlation

CPPPO Model Validation

- Ground Experiment
  - NASA Glenn LH_2 tank self pressurization testing (29% fill level)



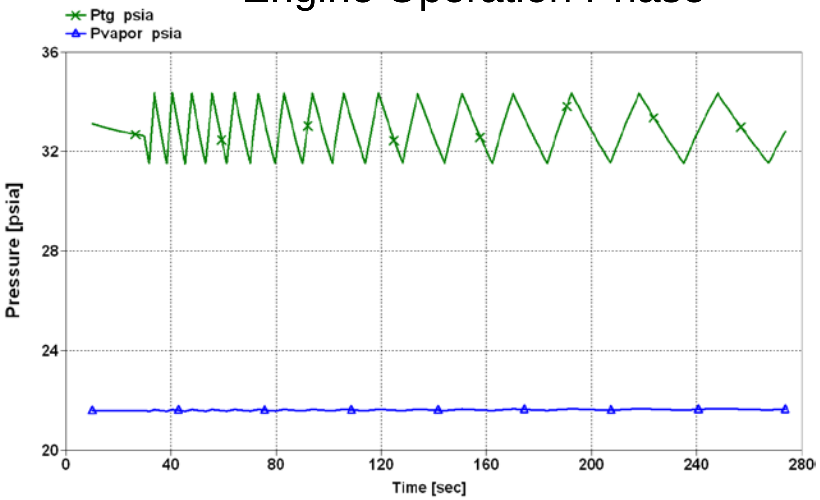
Using published heat transfer rates from test data

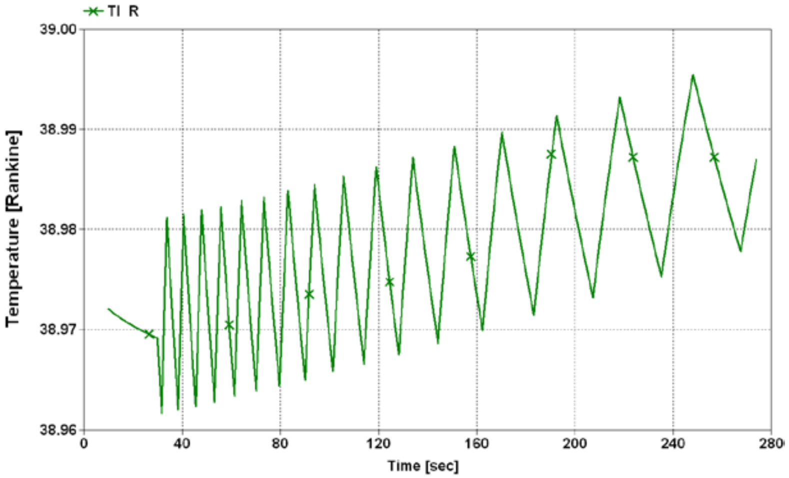


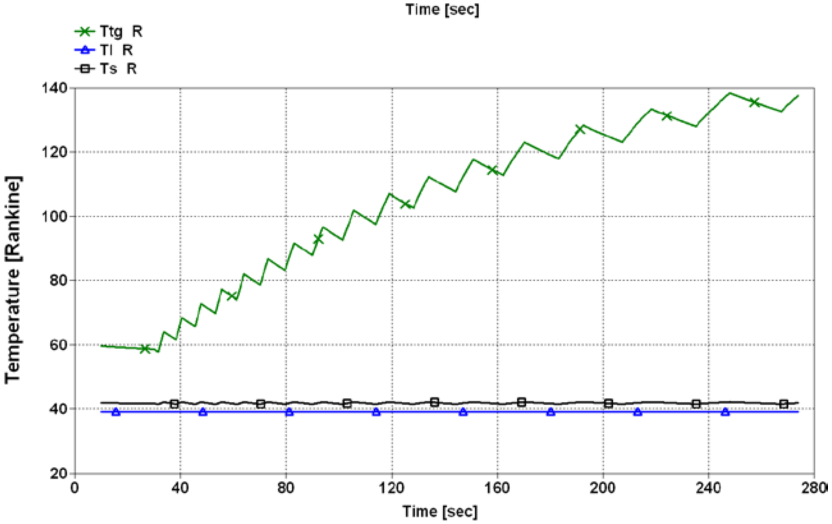
Increasing heat transfer rate to ullage gas by 20%

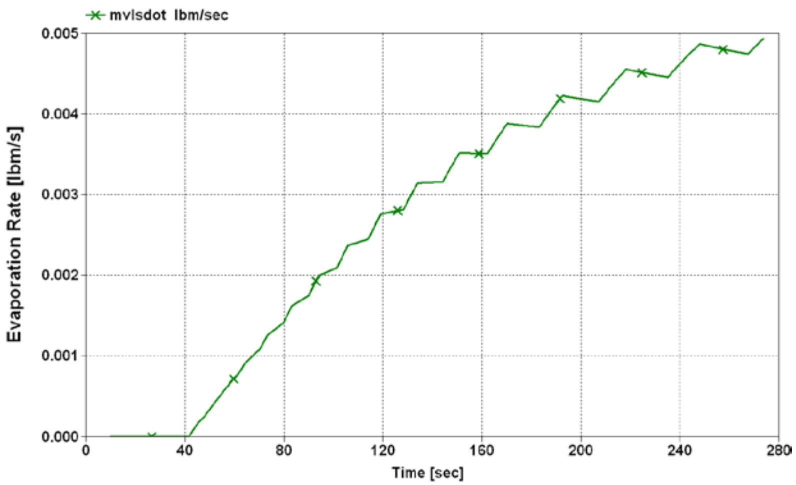
CPPPO Model Implementation

- Applied to Altair Descent Module
  - Engine Operation Phase





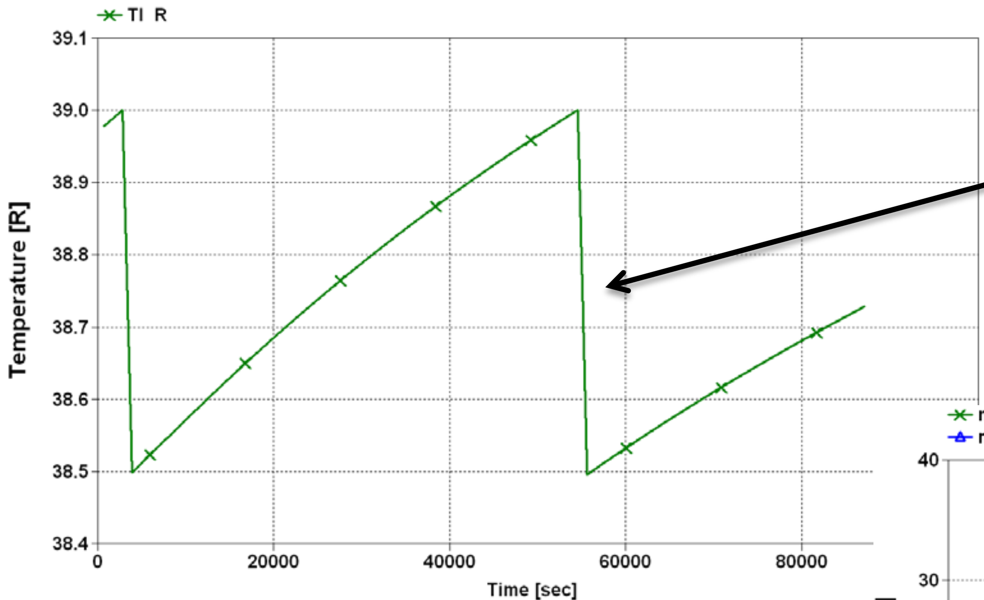




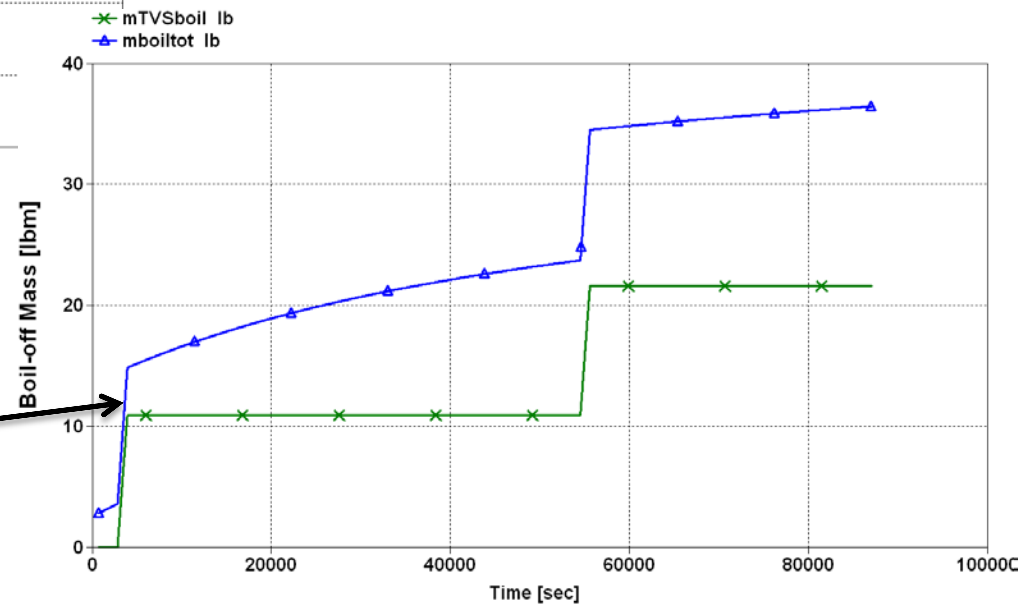
Cryogenic Propellant and Pressurization Modeling

♦ CPPPO Model Implementation

- Applied to Altair Descent Module
  - In-Space Coast Phase



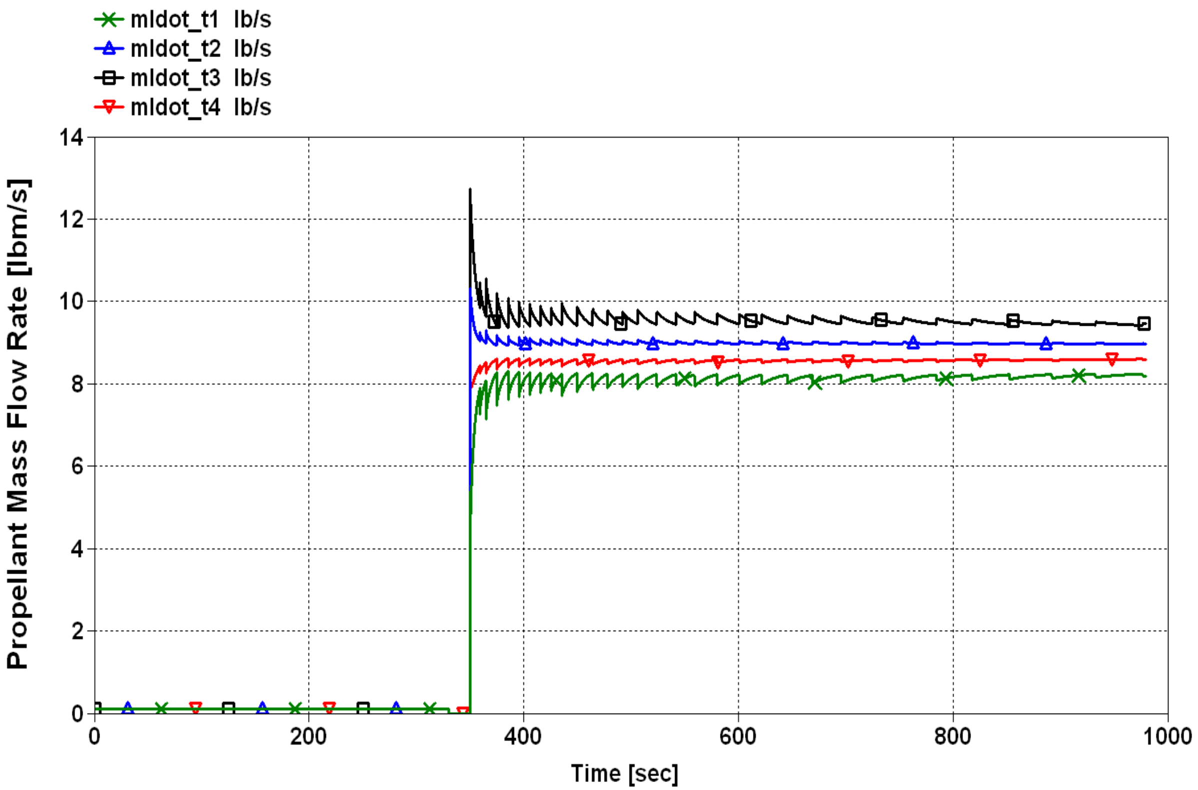
Thermodynamic Vent System operation to maintain LH_2 temperature during coast



Total boil-off mass: TVS boil-off is dumped overboard, Evaporation or Bulk Boiling remains in the ullage

CPPPO Model Implementation

- Applied to Altair Descent Module
  - Differential Tank Draining
  - Variations in pressurization and feed line resistances will cause variations in tank pressures when using multiple propellant tanks
  - Result is differential draining, possibly causing early engine cutoff and CG shifts



CPPPO Model Implementation

- Other Altair Descent Module Applications
  - Used in feed system pressure loss calculations
    - Added ability to calculate pressure loss in varying lines and components
    - Also part of differential draining analysis
  - Propellant Scavenging post landing
    - Calculated various methods of venting and heating the tanks after landing to supply residual propellant to life support and power subsystems
  - Cold Helium tank characteristics
    - Calculated real fluid property results of rapid blowdowns of cold Helium tanks
    - Results show drastic variation from ideal fluid behavior
  - Applied to alternative tank designs
    - Used code to model pressurization characteristics of alternative and novel tank designs in attempt to reduce the number of propellant tanks (and avoid differential draining issues)
  - Liquid Methane based vehicles
    - Used model to calculate some preliminary results of pressurization for liquid methane
  - Storable vehicles
    - Have updated model to also calculate pressurization properties of storable propellant vehicles such as NTO/MMH
    - NIST Refprop does not contain properties for these propellants so manually coded

Future Work

- Validation against some preliminary CFD data is underway

Acknowledgments

- Mike Martin, Skip Urquhart, and Jay Russell of MSFC/ER-22
  - Invaluable support during model development, debugging, and validation
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Questions?